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FRAGMENTATION OF METEOR BODIES

by

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[USSR]

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FRAGMENTATION OF METEOR BODIES *

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by V. G. Kruchinenko

SUMMARY

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The photometric analysis of meteors shows anomalously low values of meteor particle density and its decrease along the meteor path. It is shown, that these anomalies can be explained by the presence of gradual fragmentation. A factor of meteor fragmentation is obtained as a function of mass.

It is shown that the minimum masses of meteor particles, undergoing no further fragmentation, constitute $10^{-4} \div 10^{-6}$ g. A distribution function by masses is obtained for meteor bodies, taking into account the fragmentation factor.

Author

* * *

Analysis of the base meteor photographs provides the possibility of obtaining the velocity heights, the mass decelerations and other characteristics of meteor bodies at various points of their path. Utilizing these data and the equations of physical theory of meteors, it is possible to determine the density of the terrestrial atmosphere in the 80 — 120 km altitude range by assigning oneself the density of the meteor body.

With the availability of data on the density of the terrestrial atmosphere, obtained with the aid of rockets and satellites, significant

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* DROBLENIYE METORNYKH TEL

deflections of meteor data from those obtained by rockets were revealed; they vary with height and depend on the assumed density of the meteor body as well as on the brightness of meteors themselves. Thus, the curve of atmosphere density variation, obtained by the bright meteors and bolides, shows a significant deflection from the mean curve obtained from rocket data, though its inclination is the same. Therefore, the values of atmosphere density gradient, obtained by both methods, are in agreement. The curve discrepancy may be reduced to minimum by decreasing the density of meteor bodies to 1.0 — 0.01 g cm^{-3}. Still greater anomalies are obtained for weak meteors (to $+3^m$, sometimes to $+4^m$), photographed by Super-Schmidt cameras [1]. Observed for most of these meteors are the too great deceleration and mass loss at vaporization, which can not be explained by atmosphere density variations. All these phenomena are explained in [1] by a gradual fragmentation of meteor bodies, having a porous and friable structure. Such kind of anomalies are also observed for bright meteors, to which it will be referred in the present work. The distinction apparently consists only in that among bright meteors (brighter than 0^m), their lesser percentage is observed with anomalous characteristics. At any rate, it is quite clear that the parameters of the upper atmosphere, obtained with the aid of rockets, are known much better than the properties of meteors and meteor bodies. Utilizing the atmosphere densities from rocket data, it is possible to derive specific conclusions on the properties of meteor bodies.

For most of meteors endowed with noticeable deceleration, the densities are obtained very low ($10^{-1} - 10^{-3}$ g cm^3). This, and other anomalies, to which it was referred above, disappear, provided one assumes that we have to do with poorly packed "dust balls" or with bodies of * porous structure, already disintegrating at low aerodynamic pressure of $\sim 10^4$ dyne cm^{-2} into separate "grains" or fragments with $\sim 10^{-4} - 10^{-5}$ g. mass, rather than with durable stone or iron meteor bodies [3]. These fragments are most probably endowed with normal density, and the vaporization of every one of them is subject to the meteor physics equation for a single noncrushing meteor body. The fragmentation process progresses

* (see [2])

with the increase of aerodynamic pressure; part of fragments, undergoing a greater deceleration than the main meteor body, form the meteor tail. The latter appears on photographs obtained with a shutter in the form of light patches between meteor strokes. Such photographs are fairly often encountered. Moreover, meteors with clearly expressed tails were more than once visually observed. [4, 5].

Results of Analysis of Meteor Photographs.- Let us examine the the results of kinematic and photometric processing of photographs of five selected meteors with clearly expressed deceleration, photographed at observation stations of the Astronomical Observatory of Kiyev University (Lesniki and Tripol'ye) in the years 1958 and 1959, using NAFA-3c/25 cameras. The masses of meteor bodies are determined as a result of integration of photometric curves $I = I(t)$

$$M = \frac{2}{\tau_0} \int_t^{t_k} \frac{I}{v^3} dt, \qquad (1)$$

where M is the mass of the meteor body at the point corresponding to the time t; t_k is the moment of meteor vanishing; I is the intensity of meteor radiation; τ_o is the luminosity factor (the fraction of kinetic energy having passed into radiation in the visible part of the spectrum); v is the meteor velocity. The densities of meteor bodies are determined by the deceleartion $\dot{v}$, as is well known :

$$\delta = \Gamma^{3/2} A^{3/2} \frac{\rho^{3/2} v^3}{\dot{v}^{3/2} M^{1/2}}, \qquad (2)$$

where Γ is the drag coefficient; ρ is the atmosphere density at the given height according to rocket data [6]; A is the form factor (coefficient of shape)

$$A = \frac{S_0}{V_0^{2/3}} \left(\frac{M_0}{M}\right)^{2/3-\mu};$$

S_0, V_0, M_0 are respectively the cross section, volume and mass beyond the atmosphere; μ is the parameter of shape [7], linking the mass and cross section variations in the process of meteor body vaporization

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$$S / S_0 = (M / M_0)^{\mu}. \qquad (3)$$

According to (3), we have at vaporization of a noncrushing meteor body

$$2/3 \geqslant \mu \geqslant 0.$$

The results of computations, conducted by formulas (1) and (2), are compiled in Table 1 hereafter.

TABLE 1

№ of метеор	M_i, g	δ_i, g см$^{-3}$
17	0,780	(M_0)
	0,559	0,0490
	0,471	0,00162
	0,359	0,00153
18	0,250	(M_0)
	0,160	0,0316
	0,136	0,0210
	0,112	0,0136
	0,0879	0,00933
	0,0319	0,00400
24	0,520	(M_0)
	0,245	0,00310
	0,239	0,000877
	0,224	0,000600
	0,208	0,000561
	0,168	0,000190

№ of метеор	M_i, g	δ_i, g см$^{-3}$
40	0,0272	0,346
	0,0256	0,124
	0,0248	0,0854
	0,0216	0,0374
	0,0176	0,00600
42	0,110	(M_0)
	0,0759	0,000964
	0,0727	0,000565
	0,0655	0,000400
	0,0559	0,000253

N. B.- Here M_i and δ_i are respectively the masses and the density of the meteor body at points of meteor's path, for which the deceleration is known; M_0 is the mass of the meteor body at the point of its appearance on the film.

It should be noted that for the computations, it was admitted that $A = 1.21$ and $\mu = 2/3$. This is valid for spherical meteor bodies, not changing their shape in the vaporization process. It may be seen from Table 1, that anomalously low densities of meteor bodies are obtained, which, moreover, decrease in time. How can we explain such results? For the computation of densities of meteor bodies we admitted that drag coefficient $\Gamma = 0.5$. Speaking of vaporization of a single meteor body, such results cannot be explained by errors in the assumed value of Γ.

Nor can this be explained by errors in the density of the atmosphere or deceleration velocities and masses of meteor bodies.

The relative error in the computation of the density of the meteor body by formula (2) can be obtained from the expression

$$\frac{\Delta\delta}{\delta} = 1{,}5\sqrt{\left(\frac{\Delta\Gamma}{\Gamma}\right)^2 + \left(\frac{\Delta\rho}{\rho}\right)^2 + \left(2\,\frac{\Delta v}{v}\right)^2 + \left(\frac{\Delta\dot{v}}{\dot{v}}\right)^2 + \left(\frac{1}{3}\,\frac{\Delta M}{M}\right)^2}.$$

In the right-hand part of the formula (under the radical) the addend $(\Delta A/A)^2$, concerning the relative error in the assumed value of the coefficient of shape, has been dropped. This was done in connection with the fact, that at $\mu \neq 2/3$ the measurement range of A is sufficiently great (we shall pause at that below in more detail). If we admit the maximum relative errors

$$\frac{\Delta\Gamma}{\Gamma} = \pm 1{,}0,\ \frac{\Delta\rho}{\rho} = \pm 1{,}0,\ \frac{\Delta v}{v} = \pm 0{,}02,\ \frac{\Delta\dot{v}}{\dot{v}} = \pm 0{,}3,$$

$$\frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta I}{I}\right)^2 + \left(3\,\frac{\Delta v}{v}\right)^2} = \pm 0{,}10$$

(with the admission, when computing $\Delta M/M$, that the error in the determination of the stellar magnitude of the meteor attains $\pm 0.5^m$), we obtain

$$\Delta\delta/\delta \approx \pm 2{,}2.$$

This means, that when determining the densities of meteor particles by the given method, one may err several times as a maximum, but in no case 100 times or more.

Perhaps such results can be explained by the fact that the admitted value of A was 1.21, whereas in reality this is function of the parameter μ, which varies in the process of vaporization? Let us turn directly to the results obtained. Let us pause first of all at the fact that the densities of meteor particles decrease with time. Assume that this decrease is linked with the variation of the parameter A. Indeed, it follows from formula (2) that

$$\frac{\delta_i}{\delta_1} = \left[\left(\frac{M_1}{M_i}\right)^{2/3-\mu}\right]^{3/2} = \left(\frac{M_1}{M_i}\right)^{1-3/2\mu}, \qquad (4)$$

that is, the density at any point of the path δ_1 will not remain constant and equal to the initial density δ_0, if $\mu \neq 2/3$. The value of may be estimated for each of the five meteors, comparing the dependences of the form $\lg \delta_i / \delta_1 = f(\lg M_1 / M_i)$, obtained according to data of Table 1, with the expression (4). To that effect we plotted the graphs (Figs. 1 – 5), approximated by the most convenient dependences. The results of calculations are compiled in Table 2.

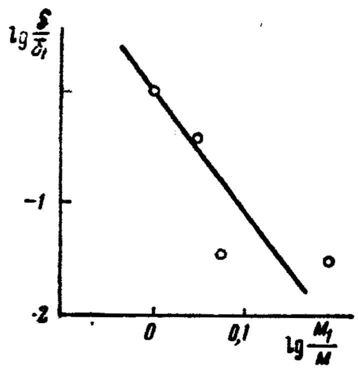

Fig. 1

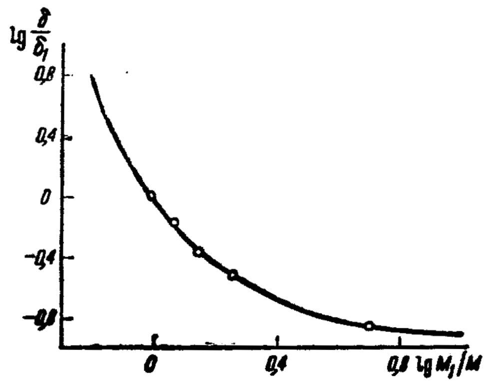

Fig. 2

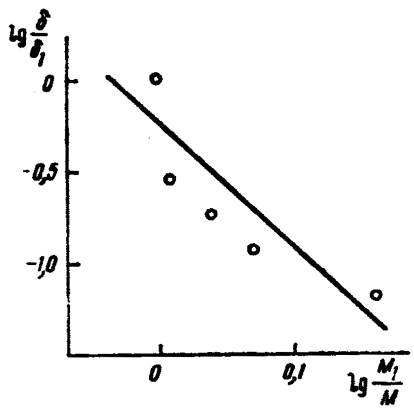

Fig. 3

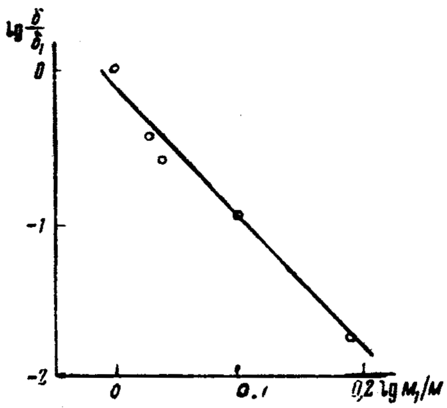

Fig. 4

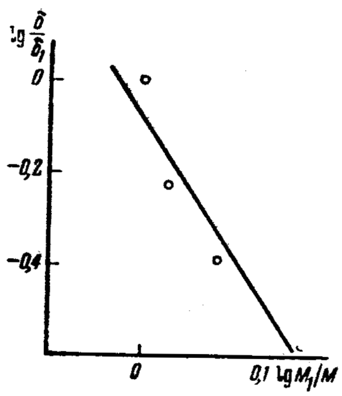

Fig. 5

The densities of meteor bodies at points of meteor appearance are given in the last column of Table 2. They were computed in the assumption, that their decrease took place along the entire path in the same fashion as it did over the portion where the deceleration is determined.

TABLE 2

№ of meteor	$\lg \delta_i/\delta_1$	μ	δ_0, г см$^{-3}$
17	$-3{,}6 \lg M_1/M_i$	3,1	0,54
18	$(M_1/M_i)^{-1,26} - 1{,}0$	1,5—2,6	0,60
24	$-7 \lg M_1/M_i - 0{,}3$	6,0—25	0,81
40	$-9{,}4 \lg M_1/M_i - 0{,}1$	5,7—10	—
42	$-4{,}3 \lg M_1/M_i$	3,5	0,016

It follows from the Table, that to explain the decrease of meteor body densities, the "parameter" μ must be a function of M_1/M_i and it must take unrealistically high values, which become absurd in the case of vaporizing noncrushing meteor body.

The thus obtained very low densities of meteor bodies, just as their decrease in the process of vaporization, can be explained without any sorts of complications, provided we postulate the fragmentation. In the first approximation we may assume that the body disintegrated into n equal parts. The deceleration equation for each separate fragment has the form

$$\frac{dv_i}{dt} = -\Gamma \frac{A\rho v^2}{\delta^{2/3} M_i^{1/3}} = -\Gamma \frac{A n^{1/3} \rho v^2}{\delta^{2/3} M^{1/3}}$$
$$(M = nM_i).$$

The true density of the meteor body is

$$\delta^* = \frac{\Gamma^{3/2} A^{3/2} \rho^{3/2} v^3}{\dot{v}^{3/2} M^{1/2}} n^{1/2} = \delta_i n^{1/2}. \qquad (5)$$

Hense, we may see that without accounting the fragmentation the obtained densities δ_i will be underrated by $n^{1/2}$ times. Naturally, the density of the matter δ^* remains constant over the entire meteor path, while δ_i depends on n, which varies in the process of vaporization. If n should increase in time, that is if the fragmentation were progressive or gradual, δ_1 would decrease. Such is the case for the five meteors brought up. But if n decreased, or somehow fluctuated, δ_i would then either increase or vary periodically. Such cases are also known (see [8] on page 57).

The number n of particles from (4) and (5) can be expressed as a function of mass variation

$$n = (M_1 / M_i)^{3\mu - 2}. \qquad (6)$$

As may be seen from Table 2, $\mu \gg 2/3$ for all the investigated meteors and it varies in the process of vaporization. In the given case μ characterizes only the intensity of the fragmentation process.

From (6) we may obtain the mean dimension of an elementary fragment (subsequently — noncrushing), if we assume that at the end of meteor path (that is at the last measured point), the meteor body itself has already completely disintegrated, while the remaining fragments continue to vaporize. It is found, that for the five investigated meteors

$$\frac{M_k}{n} = 10^{-4} \div 10^{-6} \text{ g},$$

where M_k is the mass of the meteor body at the end of the path. Analogous results were obtained from different considerations in [3, 9].

The question linked with the fragmentation of meteor bodies may be studied more strictly if we set ourselves a distribution law for crushed fragments by masses. For example, it was shown in [10, 11], that there are many cases, in which the distribution of logarithms of particle dimensions or of logarithms of their masses is approximately subject to the Gauss distribution law. An identical (logarithmically normal) law of particle distribution by masses was obtained in [12] for a random, indefinitely continuing process of particle fragmentation. In deriving this law, it was assumed, in particular, that the rate of particle fragmentation is not a function of the mass of crushing particles. If this rate should either decrease or increase with the reduction of their sizes, this law would apparently be inapplicable [12]. It would in all probability be nearer the inversely exponential.

If we admit, however, that for a swarm, formed by disintegration of the main body of mass M, the distribution of particles by masses should be subject to the normal logarithmic law, the number of all particles would then be

$$n = \frac{n(\overline{\lg M})}{\sigma\sqrt{2\pi}} \int\limits_{\lg M_{\min}}^{\lg M} \exp\left\{-\frac{(x-x_0)^2}{2\sigma^2}\right\} dx. \qquad (7)$$

The expression (7) gives the number of particles at some specific moment of time. The number <u>n</u> will vary in time, whereas the distribution law will remain the same. A preliminary calculation of fragment's mean mass, taking into account (7) at $\sigma \approx 0.427$ [10], gives a value $\sim 10^{-5}$ g.

The vaporization equation for a body in process of fragmentation may be approximately written in the form

$$\frac{dM}{dt} = -\frac{\Lambda}{2Q}\bar{A}\delta^{-2/3}n^{1/3}\rho v^3 \cdot M^{2/3}$$

or, taking into account (6) (8)

$$\frac{dM}{dt} = -\frac{\Lambda}{2Q}\bar{A}M_0^{\mu-2/3}\delta^{-2/3}M^{4/3-\mu}\rho v^3,$$

where Λ is the heat transfer coefficient; Q is the vaporization heat; $\bar{A}$ is the mean coefficient of shape of fragments participating in the vaporization.

It follows from (8) that the vaporization rate of a meteor body in process of fragmentation will be $n^{1/3}$ times higher than that for a noncrushing one with an identical mass.

It should be noted that in all probability the fragmentation of meteor bodies takes place already at the point of meteor appearance on the photofilm. The low values of δ_0, ıor example, as evidence of that (see Table 2 for the computed values δ_0 for the beginning of trajectory). The aerodynamic forces, to which the meteor bodies are subject at points of appearance, are respectively equal to $1{,}6 \cdot 10^4$; $0{,}67 \cdot 10^4$; $0{,}68 \cdot 10^4$; $2{,}4 \cdot 10^4$; $9{,}8 \cdot 10^4$ $9.8 \cdot 10^4$ dyne cm^{-2}. They are computed after the approximate formula $p \approx \rho v^2$. These pressures are also computed for other meteors. It is found that they differ little from one another. Thus, for 45 meteors (of which 29 were obtained in Kiyev [13, 14] and 16 — in Odessa [15], at point of appearance we have

$$\rho v^2 = (1{,}8 \pm 1{,}2) \cdot 10^4 \text{ dyne cm}^{-2}$$

This is evidence of very friable and unstable meteor bodies. For comparison we may point out, that the durability of a calcareous solution and pumice stone (at static loading) constitutes 10^7 dyne cm^{-2}, and that of a sandstone is of 10^8 dyne cm^{-2}.

Meteor Path Length.- The theoretical value of meteor path length in the absence of fragmentation can be obtained from the vaporization equation

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$$Q\frac{dM}{dt} = -\frac{1}{2}\Lambda S\rho v^3,$$

or, taking into account (3)

$$Q\frac{dM}{dt} = -\frac{1}{2}\Lambda A_0 M_0^{2/3-\mu} M^{\mu}\rho v^3. \qquad (9)$$

Let L_i be the length of meteor path from the initial point to any i-th point, L — the total length of the given meteor (up to the final point). The atmosphere density corresponding to the height H_i, is

$$\rho(H_i) = \rho_0 \exp\left(-\frac{H_i}{H^*}\right). \qquad (10)$$

Multiplying and dividing the right-hand part of (10) by $\exp(-H_1/H^*)$, where H_1 is the height of meteor appearance, H^* is the height of the uniform atmosphere, we shall obtain

$$\rho(H_i) = \rho(H_1)\exp\left(\frac{H_1 - H_i}{H^*}\right).$$

Since $H_1 - H_i = L_i \cos Z_R$, where Z_R is the zenithal distance of the radiant,

$$\rho(H_i) = \rho(H_1)\exp\left(\frac{L_i \cos Z_R}{H^*}\right).$$

Substituting this into (9) (taking into account that $v dt = dL_i$) and integrating it over M from M_0 to 0, and over L_i from 0 to L, we shall obtain

$$L = \frac{H^*}{\cos Z_R}\ln\left[1 + \frac{2QM_0^{1/3}\delta^{2/3}\cos Z_R}{\Lambda A_0 H^*(1-\mu)\rho(H_1)v_0^2}\right]. \qquad (11)$$

In computing L by this formula we have admitted that $Q = 8\cdot 10^{10}$ erg g^{-1}; $\delta = 3$ g cm^{-3}, $\Lambda = 0{,}5$, $A_0 = 1{,}21$, $\mu = 0{,}5$, $H^* = (6{,}5 \div 8{,}5)\cdot 10^5$ cm (as a function of H_1). M_0, v_0 and Z_R are known from analysis of photographs. L_{theor} was computed by (11) for 45 meteors [13 – 15] and compared with observation data on $L_{obs} = (H_1 - H_2)/\cos Z_R$, where H_2 is the height of meteor vanishing. The quantity $F = L_{obs}/L_{theor}$, characterizing the decrease of the observed meteor length vs its theoretical value. We designate this quantity, as formerly, the fragmentation factor. The results of these computations are plotted in the form of histograms in Fig. 6. The maximum number of meteors has $F \approx 0.3$, with the bulk of meteor body masses having values from 0.1 to 0.2, while the meteor maximum has a mass of ~ 1.0 g. For other values of masses F will be different. For example, for meteor bodies with masses of $\sim 10^{-5}$ g, the maximum of meteors will have $F = 1.0$, and for masses of $\sim 10^{-3}$ g it will have $F = 0.5$ [16]. As the mass increases, F will decrease, that is the number of "fragmentizing" meteor bodies will grow. The dependence F (M) is plotted in Fig. 7. The fragmentation maximum (minimum of F (M)) is sustained by bodies with masses of $\sim 10^{-1}$ g. With farther increase of mass the number of fragmentizing bodies decreases statistically. This is natural, since during the transition into region of coarser bodies, the asteroid matter component is felt stronger and stronger, this matter being denser and more resistant that the matter of comet origin. The dependence of fragmentation factor on the mass is approximated by the function

$$[0{,}056(\lg M)^2 + 0{,}097 \lg M + 0{,}09]^{1/2}. \qquad (12)$$

Fig. 6

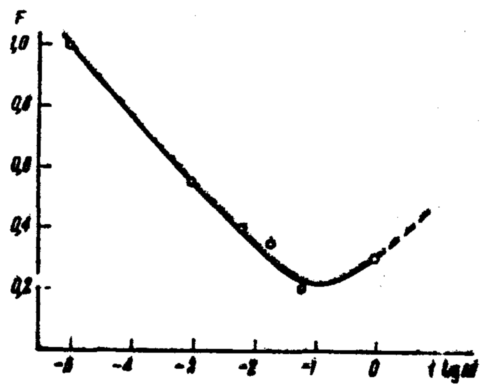

Fig. 7

Distribution Function of Meteor Bodies by Masses, taking into Account the Fragmentation.- In order to derive the distribution function by masses, f (M) dM, we shall take advantage of the fact [7], well known from visual observations, that the number of meteors grows in geometrical progression with the increase of stellar magnitude, that is

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where A (m) dm is the number of meteors in the range of stellar magnitudes from m to m + dm.

The intensity of meteor radiation will grow with the increase of fragmentationm that is, it will be inversely proportional to F (M) [16]

$$\frac{I_m}{I_0} = 2{,}512^{-m} = \left[\frac{M(m)}{M(0)}\right]^{-x} \frac{F[M(0)]}{F[M(m)]} \tag{14}$$

We may write with a precision to the sign

$$f(M)\,dM = A(m)\,dm.$$

Utilizing the Pogson dependence, we may write for meteor of a stream

$$I = \mathrm{const}\,\frac{M^x v^y \cos Z_R}{F(M)}.$$

From the expression (14), we determine m = m (M)

$$m(M) = -2{,}5\ \lg\ \{[M\,/\,M(0)]^x F[M(0)]\,/\,F(M)\}, \tag{15}$$

where M (0) is the mass of the meteor body creating a 0^m meteor. From (15), and taking into account (12), we have

$$dm(M) = -1{,}08\left[\frac{x}{M} - \frac{0{,}011 \ln M + 0{,}021}{M \cdot F^2(M)}\right] dM,$$

$$A[m(M)] = \frac{A(0)M^{x\chi}(0)}{F_0^{x}}\,\frac{F^{\chi}(M)}{M^{x\chi}} \quad (\chi = 2{,}5 \lg \varkappa).$$

In the given case, the distribution of meteor bodies by masses, taking into account the fragmentation for the meteors of the shower (v = const), will have the form

$$f(M)\,dM = \frac{B}{M^s}[F^{s-1}(M) - (0{,}011 \ln M + 0{,}021)F^{s-3}(M)]\,dM, \tag{16}$$

where B is a certain constant, F (M) is given by the expression (12) $s = 1 + 2{,}5x \lg \varkappa$, $x \approx 1{,}0$. If the dependence (16) is presented in the usual form

$$f(M)\,dM = BM^{-s_0}dM,$$

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where s_0 is the parameter s, computed taking into account the fragmentation, we have

$$s_0 = s + \lg[F^{s-1}(M) - (0{,}011 \ln M + 0{,}021) F^{s-3}(M)] / \lg M. \quad (17)$$

It is easy to see that $s_0 \geqslant s$.

Presented in Table 3 are the values of s_0 for $s = 1.50; 2.00$ and 2.50 for various values of the mass, computed by the formula (17).

TABLE 3

	s_0				
s	$M = 10^{-4}$g	10^{-3}g	10^{-2}g	10^{-1}g	1 g
1.5	1.50	1.52	1.57	1.79	1.60
2.0	2.01	2.06	2.18	2.63	2.20
2.5	2.53	2.60	2.79	3.46	2.80

Therefore, when failing to take into account the fragmentation, we systematically underrated the value of the parameter s, and by the same token, we overrated the role of coarser meteor bodies.

****** THE END ******

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252	LIBRARY	[2]
256	FREAS	
660	GI for SS	[5]

NASA HQS

SS	NEWELL, CLARK	
SP	STANSELL	
SG	NAUGLE	
	SCHARDT	
	ROMAN	
	SMITH	
	DUBIN	
SL	LIDDEL	
	BRUNK	
	GAUGLER	
	FELLOWS	
	HIPSHER	
	HOROWITZ	
SM	FOSTER	
	ALLENBY	
	GILL	
	BADGLEY	
RR	KURZWEG	
RV-1	PEARSON	
RTR	NEILL	
ATSS-T	SCHWIND	[4]
	ROBBINS	
WX	SWEET	

OTHER CENTERS

AMES R. C.

SONETT		[5]
94035		[3]

LANGLEY R.C.

160	ADAMSON	
235	SEATON	
213	KATZOFF	
	DAVIS	
	WINEMAN	
231	O'SULLIVAN	
242	GARRICK	
303	ROBERTS	
338	BRASLOW	
185	WEATHERWAX	[2]

UCLA

COLEMAN

U C BERKELEY

WILCOX